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TRACKING PERFORMANCE REQUIREMENTS FOR ROTORCRAFT INSTRUMENT APPROACHES TO REDUCED MINIMA
Phase 1 - Preliminary Study

by

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Institute for Aerospace Research

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TRACKING PERFORMANCE REQUIREMENTS FOR ROTORCRAFT INSTRUMENT APPROACHES TO REDUCED MINIMA
Phase 1 - Preliminary Study

EXIGENCES RELATIVES AUX PERFORMANCES DE SUIVI D'APPROCHE AUX INSTRUMENTS D'UN GIRAVION AFIN DE RÉDUIRE LES MINIMA
Phase 1 - Étude préliminaire

by

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ABSTRACT

The ability to track approach guidance (position and speed) to a low decision height (50 feet) when performing a steep instrument approach (6 to 9 degrees) in a rotorcraft clearly has a profound effect on the success of the approach. This report describes a preliminary attempt to define approach tracking standards for such approaches and includes a systematic data base upon which such standards can be based. This data base was generated in a flight experiment in which qualified rotorcraft certification test pilots evaluated the suitability of arriving at the decision height with various combinations of approach tracking error. The magnitude of tracking errors that are compatible with satisfactory pilot workload in the transition to hover and landing is well defined and tracking within these error bounds is clearly within the limits of current technology. The experiment was performed on the National Research Council of Canada's Bell 205 Airborne Simulator.

RÉSUMÉ

La capacité de suivre la trajectoire d'approche d'un giravion (position et vitesse) jusqu'à une faible hauteur de décision (50 pieds) au cours d'une approche aux instruments à forte pente (6 à 9 degrés) a, de toute évidence, une influence déterminante sur le succès de cette approche. Le présent rapport d´écrit une tentative préliminaire visant à d´finir des normes de suivi de l'approche pour de telles approches et il comprend une base de donnés syst´matique sur laquelle on peut baser ces normes. Cette base de données a été mise sur pied dans le cadre d'un programme d'essais en vol dans lequel des pilotes d'essai qualifiés pour la certification des diravions ont évalué dans quelle mesure on pouvait arriver à la hauteur de décision selon diverses combinaisons d'erreurs de suivi de l'approche. L'importance des erreurs de suivi qui sont compatibles avec une charge de travail satisfaisante du pilote pendant la phase de transition au vol stationnaire et l'atterrissage est bien définie et le suivi à l'intérieur de cette plage d'erreur est sans contredit réalisable au moyen de la technologie actuelle. Le programme d'essais a été effectué à l'aide du simulateur embarqué à bord du Bell 205 du Conseil national de recherches du Canada.

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1.0 Introduction

1.1 Background

The Flight Research Laboratory (FRL) of the Institute for Aerospace Research (IAR) (formerly the National Aeronautical Establishment (NAE)), National Research Council of Canada has been actively engaged in jointly funded experiments with the United States Federal Aviation Administration (FAA) since early 1980. These experiments, designed to address rotorcraft handling qualities requirements for flight under Instrument Flight Rules (IFR), have been performed under a Memorandum of Agreement with the FAA, AIA-CA-31. References 1 and 2 describe some of the previous phases of this program.

One of the major areas of investigation in the joint program with the FAA has been the operational feasibility of steep (6 degrees and above) decelerating instrument approaches to a decision height of 50 feet coincident with 20 knots groundspeed. During these studies it became apparent that the conventional standards of approach performance (also described as allowable flight technical errors) could not be extrapolated to the 50 foot decision height case. The approach tracking standards which allow an acceptable transition to visual flight and manoeuvring to a landing pad hover from the 50 foot decision height form an underlying constraint to the reduced minima approach concept.

1.2 Aim And Scope Of The Program

The overall objective of the tracking standards program was to provide a systematic data base upon which the standards for satisfactory tracking performance of decelerating instrument approaches to reduced minima can be based. These standards, of course, would also be used in follow-on research regarding these types of operations. The aims of the preliminary phase of the program were threefold; first, to determine the experimental approach for producing this data base; second, to evaluate the approximate magnitude of errors in height from a nominal glideslope, and speed errors from a nominal deceleration profile, which would be acceptable at breakout for the transition to the visual approach to landing; and third, to examine some of the variables which govern the level of these acceptable errors.

Because of the preliminary nature of this program, tests were concentrated on a glideslope of nine degrees, with a brief investigation carried out on a glideslope of six degrees. Furthermore, on the majority of approaches the breakout at decision height was in the presence of good visual conditions, with only a limited number of data points achieved in degraded visibility. Also, the approach and landing pad marking was of an austere form, with no attempt made to provide variable intensity approach and landing area marking.

2.0 The Airborne Simulator

Experiments were carried out using the IAR Airborne Simulator (formerly the NAE Airborne Simulator), an extensively modified Bell 205A-1 with special fly-by-wire capabilities that have evolved over the last eighteen years (Figure 1). The standard hydraulically boosted mechanical control actuators on this aircraft incorporate servo-valves that can be positioned either mechanically from the left (safety pilot) seat or

electrically by the aircraft computing system. Evaluation pilot (right seat) control inputs from either conventional cyclic and pedals or integrated side arm controllers (conventional controls were used throughout this particular program) are measured and fed to a computing system consisting of two LSI 11/73, one Falcon microprocessor and other assorted hardware. Full authority fly-by-wire actuator commands are generated by software which manipulates inputs made by the evaluation pilot and data from a full suite of aircraft state sensors.

Additional modifications to the Airborne Simulator have been incorporated to increase the simulation envelope of the facility. The standard Bell 205 stabilizer bar was removed in order to quicken the control response of the teetering rotor system, and the cyclic-to-elevator link was replaced with an electro-hydraulic actuator, although the elevator remained fixed in a neutral position for this program. Reference 3 provides a detailed description of the Airborne Simulator.

In order to simulate instrument flight conditions visually, an IMC Simulator manufactured by Instrument Flight Research Incorporated, Columbia, S.C. was employed. The "simulator" consisted of goggles with lenses that incorporated liquid crystals to vary the lens opacity. These goggles were worn by the evaluation pilot and were adjusted to provide a narrow field of unobstructed view of the flight instruments with the remaining peripheral view highly obscured. An electrical input to the goggles, provided by the aircraft computing system, caused the obscured peripheral view to clear at 50 feet above ground level, coincident with the approach decision height.

2.1 Cockpit Display

On all approaches, primary approach information was displayed in a combined form on a light emitting diode (LED) matrix electronic attitude and direction indicator (EADI) as shown in Figure 2. The 5 inch by 5 inch display consisted of LED's organized into a matrix with a density of 64 x 64 pixels per square inch. Raw data displays of errors in localizer, glideslope, and speed were provided, as well as a three axis flight-director for the approach. Reference 1 details the design of the flight director. Warning of the decision height was accomplished by flashing the radio altitude box on the left side of the display and the flight-director command symbol. This flashing started at 10 feet above decision height, and remained flashing until decision height was reached.

In this program, the errors in glideslope and/or speed desired for the experimental data base were obtained by feeding biases into the command signal for the flight director. The raw display accurately reflected deviations from the nominal glideslope and speed deceleration profile throughout the approach.

2.2 Control Characteristics and Stability Augmentation

The analogue control force feel system of the Airborne Simulator was set up to provide 1/2 lb breakout and 1/2 lb/in stick force gradient for the pitch and roll axes. A slow rate trim for pitch and roll was provided through a "coolie hat" switch on the cyclic control stick. No trim force release function was provided. The collective lever was a typical adjustable friction type with no force gradient or perceptible breakout force.

The yaw pedal force feel system was adjusted to provide just enough breakout and gradient forces to allow good self-centring of this control. Two yaw axis modes were available during the approach, a simple rate damped mode and a heading hold system. The heading hold mode completely eliminated the need for yaw pedal inputs during the approach.

In this experiment, the Airborne Simulator was configured to represent dynamic characteristics of typical modern rotorcraft that are certificated for instrument flight. Levels of pitch and roll rate damping similar to those of an augmented Sikorsky S-76 were incorporated. Figure 3 shows the overall rate damping derivatives of the Airborne Simulator as a function of speed. For comparison purposes, the "SAS on" rate damping derivatives of the standard S-76 are also included on the figure. Inter-axis control coupling between all aircraft axes were essentially eliminated by the use of simple control cross feeds to the respective control axes. This characteristic is also similar to a fully augmented S-76.

3.0 Approach Description

Steep (six and nine degree) decelerating instrument approaches were performed to a decision height of 50 feet by tracking a 3-cue flight director (localizer, glideslope and speed). On the majority of approaches, the evaluator tracked the flight director manually, although some approaches were flown with the aircraft coupled in all three axes. As previously mentioned, the flight director command signal was altered on each approach to lead the aircraft to a desired error state at breakout while the raw data displays truthfully reflected the error condition.

3.1 Approach Guidance

A distance measuring multiple transponder system, coupled with doppler ground speed information, was used to measure the aircraft position and provide approach guidance. Absolute accuracy of the horizontal position measurement using this system was on the order of 6 feet. Localizer and distance quantities were calculated by transforming the position information into the appropriate reference frame. Since the terrain in the approach area was relatively flat, radar altitude and distance from the touchdown zone were used to calculate glideslope position.

3.2 Deceleration Profile

All approaches were flown using ground speed calculated from a mixture of position, Doppler ground speed and acceleration measurements. The desired approach speed was initially a constant controlled by a cockpit panel selector. When this constant speed and the aircraft range to the touchdown point intercepted the deceleration profile shown in Figure 4 the commanded speed became that of the deceleration profile. Both the commanded ground speed and actual aircraft ground speed were displayed on the electronic EADI for the entire approach.

3.3 Landing Area

Approaches were flown to one of two landing pads located in an open field on relatively flat terrain. In most cases, this field was covered with snow, although blowing snow was not a factor in reducing visibility. The landing areas were marked with bright florescent orange traffic cones. Figure 5 describes the two landing pads used in the experiment, differing only in the "lead-in" markings shown for pad 'A'.

4.0 Experimental Procedure

A preliminary series of ad-hoc evaluations for this program were flown by one of the project engineers and one research pilot. The objectives of these evaluations were to determine the experimental procedure for the more formal evaluations to come and to make preliminary judgements on the magnitudes of speed and glideslope errors that were practical to evaluate. On a number of these approaches it was found that the heading of the aircraft at breakout could override the effects of all other tracking errors since large heading deviations from the approach heading, in combination with some error states, resulted in the pad not being visible at decision height. To eliminate this possible confusion in formal evaluation data, the use of heading hold on the inbound approach heading was used for the remainder of evaluations.[1]

The ad-hoc evaluations also compared the workload of transition from breakout to landing pad hover, following the manual tracking of the approach, with that of flying an autopilot coupled approach. The discussions of this issue following the evaluation concluded that during the manual tracking approach the pilot was more "in-the-loop" and could more easily make the transition to visual flight but was less aware of the tracking errors present at breakout. The autopilot approaches with takeover to manual flight at the decision height allowed the evaluation pilot more time to scan the display and be aware of the tracking errors at breakout but did require additional effort to get "into the loop" of control. Since occasional errors in position measurement gave highly undesirable aircraft reactions during the coupled approach, the majority of formal evaluations were made using manual tracking of the flight director.

Formal evaluations were flown by four pilots, including three research pilots and one rotorcraft certification pilot from the FAA. Table 1 is a summary of the flight experience of the evaluators. Each of the evaluators was asked to manually track the flight director down to decision height where the goggles cleared, and then continue the approach to a hover over the landing area. Heading hold was engaged for all approaches, resulting in close alignment of aircraft heading to the approach course at breakout[2].

On completion of each approach the evaluators were asked to rate the handling qualities and aircraft performance for the visual portion of the approach on the Cooper-Harper handling qualities rating scale shown in Figure 6, and to supply comments regarding their ratings and the task in general. Post flight

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[1] The visual acquisition of the landing pad is an issue which must be considered carefully as each IFR rotorcraft has its own inherent field of view and visibility restrictions. Clearly a Bell 205 cockpit cannot represent all possible cockpit visibility conditions and therefore this issue must be evaluated on an aircraft to aircraft basis.

[2] The possible influence of crosswinds while using heading hold mode on these approaches is discussed in Reference 1.

debriefing of all pilots was used to solicit more comments regarding the evaluations.

Evaluations were made over a wide range of glideslope and speed errors primarily for nine degree approaches however some six degree approach data was also gathered. Additional evaluations were made of the effect of having the IMC goggles remain slightly fogged throughout the "visual" segment of the approach and requiring the evaluation pilot to land in this reduced visibility condition. It was hoped that these evaluations could somehow indicate the impact of more representative conditions at breakout rather than the near-perfect visibility afforded by the clearing of the IMC goggles at decision height.

5.0 Evaluation Results

Table 2 lists the error conditions and handling qualities ratings for the formal evaluations of six and nine degree approach transitions. Table 3 summarizes the same data for the evaluations in which the IMC goggles were kept fogged at a low level throughout the "visual" segment of the approach. The corresponding pilot comments for each of these evaluations are contained in Appendix A.

5.1 Acceptable Error Boundaries

Figures 7 and 8 are plots of the handling qualities ratings corresponding to the various error states evaluated for the nine and six degree glideslope cases. For the majority of evaluations, each evaluator indicated that a handling qualities rating of 7 corresponded to an approach situation where the manoeuvres required or the time available to make the transition to visual flight was unacceptable. A rating of 6 therefore was indicative of an error state which was acceptable, although sometimes just marginally. This use of the Cooper-Harper scale may initially be perceived as significantly different from the standard interpretation since the 6-7 boundary describes whether "adequate performance is attainable with tolerable pilot workload". In general all evaluators in this program employed the strategy of limiting their flare attitude, collective commands and "quickness of response" to a level they perceived as acceptable for the transition manoeuvre. In cases where the evaluation pilots rated the transition as a 7 or above, these attitude, collective and response limits restricted the aircraft performance so that it could not stop at the desired location, thus giving the "adequate performance is not attainable" result.

As shown in the two figures, especially in the nine degree approach case, there is an envelope of acceptable errors at decision height for combinations of speed and height errors. A suggested envelope is drawn as a dashed line on Figure 7. Three unacceptable ratings (approaches #5, 78, and 94) were disregarded in the drawing of this boundary based on the pilot comments for each approach and ratings and on the conflicting comments for other approaches at similar error levels. A six degree approach envelope was determined by geometrically converting the nine degree approach glideslope error boundary to values which correspond to the same physical position relative to the landing pad on a six degree approach.

Inside the acceptable/unacceptable boundary on Figure 7 is a second boundary (a solid line) suggesting the maximum error level which still would produce Level 1 handling qualities ratings (a value of 3 or less). This second area is that in which the transition and manoeuvring after breakout were described as

"satisfactory without improvement", clearly a desirable envelope to aim for in flight director design and general operations but not the envelope of maximum allowable error. Again this boundary was geometrically converted to the six degree glideslope case.

No attempt was made to determine the boundary for being low on the glideslope at the decision height since the restricting factors for this case would be visibility and pad markings versus clearway off the approach end of the helipad.

In cases where the approach was rated as unacceptable due to being too slow, aircraft vibration occurring during the transition from forward to hovering flight was always cited as the reason for the rating. Considerations of the aircraft vibration level while going through this transition, and of the need to maintain some closure rate to the landing pad, must be made before a minimum closure speed boundary can be drawn. The impact of ambient winds must also be considered in this light. Based on the limited data gathered over the course of this experiment, a 10 knot closure rate minimum was chosen to provide a reasonable minimum closure rate on the pad. This limit was also consistent with the evaluations citing objectionable vibrations for transitions starting at speeds less than this value.

Despite some rather large localizer errors at decision height (as shown in the Table 2 data), lateral offset was not cited as the cause of an unacceptable rating or even the source of any pilot commentary. This result suggests that the lateral tracking performed during the course of the evaluations was inside an acceptable lateral error boundary for the case of heading hold approaches.

All boundaries shown on Figures 7 and 8 must be considered with the following points in mind:

1) All approaches performed in this experiment were concluded with a breakout and hover at the landing point. Such a case does not include the typical mental workload of deciding if a visual acquisition of the pad would be possible and whether a go-around should be initiated.

2) For all approaches evaluated during this experiment, the pilot was able to keep the flight director reasonably centered throughout the approach but upon breakout had reasonably large errors in approach tracking (which were indicated in the raw data display). In many operational scenarios, large tracking errors at breakout would be due to poor flight director tracking and so the pilot would have more cues that the approach was going poorly.

5.2 Visibility Considerations

Evaluations of the restricted visibility transition to hover, those approaches where the goggles were kept at a low level of fogging throughout the evaluation, were unsuccessful at determining the impact of lower visibility at breakout. For these evaluations, the pilots unanimously responded that the visual environment was totally unrealistic and in exact opposition to what the visual environment of IMC operations is like. This comment referred to the fact that the goggles tended to obliterate the fine texture close to the aircraft yet leave the horizon virtually unaffected while real IMC obliterates the horizon but leaves very close texture unaffected. The goggles were also annoying in that they obliterated the inside of the cockpit as well as

those features outside it. These comments, coupled with the deficiencies in the experimental landing pad environment, an area of low contrast with no lighting, reveal that the utility of handling qualities ratings gathered from these restricted visibility approaches is questionable at best.

Despite the problems mentioned above, certain observations made during these restricted visibility evaluations are worthy of consideration. In most cases the lead-in markings of pad "A" were found to be of little use as they were generally below the aircraft and out of sight by the time the aircraft was at the decision height. *(Lead-in markings are useful for the majority of operational environments where the actual breakout to visual conditions would be higher than 50 feet.)* On the other hand, some pilots did remark that markings and lighting which could grab the pilots attention and direct it to the centre of the landing pad would have been useful for the more difficult approach error conditions. These comments would suggest that a lighting system that is at the sides and behind the landing pad, possibly all rippling towards the pad centre, such as depicted in Figure 9, would be of benefit for these operations.

6.0 Theoretical Consideration of the Error Boundaries

An in-depth analysis of the envelopes of acceptable and satisfactory error states at decision height for the 9 degree decelerating approach was conducted on the basis of two concepts that should delineate acceptable from unacceptable states. The first concept is that the "acceptability" of a given error state at decision height is entirely related to the magnitude of intervention that the <u>pilot</u> must apply to complete the approach. This analysis compares the approach ratings to the magnitudes of control deflection and attitude change over the visual segment of the approach and to the magnitudes of deceleration and sink rate errors that were present at decision height. The second concept of analysis dealt with the capability of the <u>vehicle</u> to accomplish the remainder of the approach. This concept suggests that the "acceptability" of an error state is directly related to the percentage of available aircraft performance which must be used to complete the approach. In this regard, a parameter named the *effective flight path angle* was developed.

6.1 Pilot Intervention Analysis

There are several parameters that can be used to gauge the magnitude of the required pilot intervention during the visual segment of the approach. The analysis of the evaluation results in this program centered on the following quantities:

1. The range of collective control change used by the pilot over the visual segment of the approach, $\Delta\delta$

2. The maximum change in aircraft pitch attitude from the time of break-out at decision height to the final hover, $\Delta\theta$.

3. The sink-rate error, $\Delta\dot{z}$, defined as the difference between the desired and actual values of the sink rate of the aircraft at the decision height of 50 feet.

4. The deceleration error, $\Delta \dot{v}$, defined as the difference between the desired and actual values of the aircraft deceleration at decision height.

While cases (1) and (2) above are intuitively appealing, their analysis did not reveal significant correlation between rating level and the parameters in question. This may be in part due to the pilot imposed limits on collective activity and flare attitude which have been mentioned earlier in this report.

Figures 10 and 11 display the results of the analyses using sink rate and deceleration errors. Since the approach ratings showed a large correlation with velocity at decision height, both sink rate error and deceleration error were chosen as the y axis of plots where velocity at decision height was retained as the x axis variable. While the trends with decision height velocity are readily apparent, both plots show little if any correlation between y axis variable and rating value. Since the sink rate and deceleration errors were strongly felt to be relevant to the approach rating level, another analysis was performed to combine the two variables into a single parameter on the basis of the error in rate of change of potential and kinetic energy. This parameter, named the specific energy rate error, $\Delta \dot{e}$, was formulated as shown below:

$$\Delta \dot{e} = \Delta \dot{z} + \frac{1.6889}{g} \times (V_d \dot{V}_d - V_{dh} \dot{V}_{dh}) \qquad (1)$$

where	$\Delta \dot{z}$	=	sink-rate error at decision height (ft/sec)
	V_d	=	desired velocity at decison height (in this case 20 knots)
	$\dot{V}_d$	=	desired deceleration at decision height (ft/sec^2)
	V_{dh}	=	actual velocity at decision height (knots)
	$\dot{V}_{dh}$	=	actual deceleration at decision height (ft/sec^2)
	g	=	gravitational acceleration (ft/sec^2)

As such, $\Delta \dot{e}$ represents the error in the total rate of change of specific energy (i.e. total energy per unit weight), and can be viewed as an index of the required pilot intervention, since the pilot must adjust the aircraft sink rate and deceleration to agree with the desirable values in order to complete the approach successfully. With this parameter calculated, the earlier plots of approach rating versus decision height velocity and glideslope error were sorted into three plots with $\Delta \dot{e}$ in the ranges of 0 - 3.5 ft/sec, 3.5 - 7.0 ft/sec and those above 7.0 ft/sec. These three plots, included as Figures 12, 13, and 14, show that the all ratings with $\Delta \dot{e}$ larger than 7.0 ft/sec are unacceptable but that these values of $\Delta \dot{e}$ were only attained at larger values of velocity and glideslope error. On the other hand, the figure with $\Delta \dot{e}$ less than 3.5 ft/sec still includes a number of unacceptable approach ratings for the larger velocity and glideslope error cases, despite the fact that little pilot intervention would be required in these instances. Overall, it must be concluded that while the concept of pilot intervention intuitively is related to the acceptability of a given error state at decision height, analyses of the rating data with this concept in mind fails to clarify the fundamental basis for unacceptable approach error states.

6.2 Definition of Γ_{eff}

In conjunction with the second concept of rating analysis described earlier, a parameter called the effective flight path angle, Γ_{eff}, was developed to quantify the amount of energy present at decision height and to express the trade off between excess speed and excess height. For steady unaccelerated flight we can write an expression for the geometric flight path angle, Γ_o, as:

$$\Gamma_o = \sin^{-1}\left(\frac{Thrust-Drag}{Weight}\right) \qquad \textbf{(2)}$$

where Thrust and Drag are coincident with the flight path and a negative Γ_o signifies descending flight. If we allow acceleration to occur along the flight path, this expression becomes:

$$\Gamma_o = \sin^{-1}\left(\frac{Thrust - M \times a_{fp} - Drag}{Weight}\right) \qquad \textbf{(3)}$$

where M is the aircraft mass and a_{fp} is the acceleration along the flight path. Assuming a specific speed, and hence a constant drag, and assuming that a constant flight path angle is to be maintained (equating expressions (2) and (3)), it becomes clear that the relationship between the two thrust values is:

$$Thrust(eqn\ 3) = Thrust(eqn\ 2) + M \times a_{fp} \qquad \textbf{(4)}$$

We now define the effective flight path angle, Γ_{eff}, as the unaccelerated flight path angle (equation 2) which would occur if the thrust for the accelerated case (equation 3) were used:

$$\Gamma_{eff} = \sin^{-1}\left(\frac{Thrust(eqn\ 3) - Drag}{Weight}\right) \qquad \textbf{(5)}$$

which simplifies to:

$$\Gamma_{eff} = \sin^{-1}\left(\sin\Gamma_o + \frac{a_{fp}}{g}\right) \qquad \textbf{(6)}$$

where Γ is the unaccelerated, or geometric flight path angle as in equation (2). The parameter defined in equation (6), Γ_{eff}, relates the total geometric flight path capability of an aircraft with its ability to accelerate or decelerate. Clearly if a climbing aircraft at maximum thrust is required to accelerate, it must reduce its

geometric flight path angle yet it should maintain the same value of Γ_{eff}. In the case of descending rotorcraft, the same relationship should apply.

6.2 Γ_{eff} Formulation for Various Breakout Conditions

Using the nomenclature of Figure 15, the slant range (SR) of an aircraft from its position at decision height (DH), with a glideslope error of δH feet above the nominal glideslope Γ_a, to the landing pad can be written as:

$$SR = \sqrt{DH^2 + \left(\frac{(DH - \delta H)}{\tan(\Gamma_a)}\right)^2} \qquad \textbf{(7)}$$

and the geometric flight path angle that the aircraft must take to get to the pad, Γ_o, is[3]:

$$\Gamma_o = \sin^{-1}\left(-1 \times \frac{DH}{SR}\right) \qquad \textbf{(8)}$$

If, at decision height, the aircraft has a velocity along the flight path of V_{DH}, it must decelerate to stop at the pad over the slant range distance. This deceleration can be written as:

$$a_{fp} = -\frac{V_{DH}^2}{2 \times SR} \qquad \textbf{(9)}$$

Using equations (7), (8), (9) and (6), the effective flight path angle, Γ_{eff}, required for the rotorcraft to decelerate to the landing pad from the decision height, DH, with a velocity of V_{DH} and a height error of δH feet from the nominal glideslope Γ_a, is given by:

$$\Gamma_{eff} = -1.0 \times \sin^{-1}\left(\frac{\frac{V_{DH}^2}{2 \times g} + DH}{\sqrt{DH^2 + \left(\frac{DH - \delta H}{\tan(\Gamma_a)}\right)^2}}\right) \qquad \textbf{(10)}$$

[3] This formulation neglects the hover height which the aircraft will come to rest at prior to landing. This term could be included by subtracting that height from the decision height, DH.

6.3 Handling Qualities versus Error State Data Analysis

With the development of Γ_{eff} in mind, a plot of handling qualities rating versus $|\Gamma_{eff}|$ for all approaches (except those rated unsatisfactory on the basis of being too slow at breakout) is included as Figure 16. This figure shows that while ratings of 7 or higher (unacceptable) start to occur when $|\Gamma_{eff}|$ exceeds a value of 17 degrees, ratings of acceptable handling qualities occur for $|\Gamma_{eff}|$ up to 37 degrees. While the trend is not strongly definitive, a Γ_{eff} value of -20 degrees could be assumed as a reasonable limit for acceptable handling qualities for the transition manoeuvre.

Figure 17, a replication of Figure 7 (the 9 degree glideslope data), includes a line representing $\Gamma_{eff} = -20^{\circ}$. While this new line does delineate a majority of the acceptable versus unacceptable ratings, it does not agree with the entire data base, especially in the upper portion of the acceptable rating area. Since a boundary defined by a constant value of Γ_{eff} does not match the observed handling qualities rating trends, the empirical handling qualities boundaries developed in section 5.1 were converted to Γ_{eff} values to examine the relationship between acceptable error states and aircraft performance. The translated values of these empirical boundaries are shown in Figure 18 on the Bell 205 Γ - V diagram. The resultant boundary curves follow the general performance curve shape of the Bell 205. This behaviour, allowing larger effective flight path angles at lower speeds (and thus more descent or deceleration), suggests that the pilot is willing to use a relatively constant percentage of the vehicle maximum performance[4]. The portion of the boundaries on Figure 17 which are constant glideslope errors are responsible for the reduction of the allowable Γ at the slowest speeds on Figure 18. The high flight path angle/low speed area eliminated by the constant glideslope error portion of the boundary is an area in which the aircraft vibrations were noted as significant during the measurement of the aircraft Γ - V curves and these vibrations were also cited in the high descent/slow speed approach evaluations.

For the 9 degree glideslope evaluations performed over the course of this experiment it appears that the tracking error level the pilots determined as borderline is defined by the Γ_{eff} for approximately 5 psi torque on the aircraft Γ - V curve. The satisfactory handling qualities boundary parallels the acceptable boundary on the Γ - V diagram but follows the performance curve shape to a much lesser extent.

The error boundaries for acceptable and satisfactory handling qualities, in terms of speed and glideslope error (Figure 7), were converted to the 6 degree glideslope case by translating the boundary value of glideslope error at a given speed on the 9 degree approach diagram into the value of glideslope error required to place the aircraft in the same physical position during a 6 degree approach. A 10 knot minimum V_{CH} boundary was also used. These boundaries are plotted on Figure 8 for the 6 degree approach handling qualities data. While other boundaries could be easily drawn on the basis of the 6 degree data, the 9 degree approach generated boundary does show general agreement with the evaluation data. On the same basis, postulated error boundaries for a 12 degree glideslope approach have been generated and are included as Figure 19.

---

[4] No pilot comments were made which could be used to substantiate that this behaviour is cognitive on the pilots' part but it perhaps stems from the almost unconscious ability of pilots to judge the remaining available performance of an aircraft in a given situation.

6.4 Wind Effects on Acceptable Approach Error Levels

The Γ_{eff} analysis carried out in the last section was based purely on inertial or groundspeed related parameters. The inclusion of wind into the analysis opens a number of areas for consideration. With the low or negative airspeeds possible for approaches in tail winds, the vehicle handling qualities will degrade due to vibration and changes in vehicle dynamics. Since the time spent in this low speed regime is very limited, it may be debatable whether these changes will be acceptable during an approach. A second important consideration is the susceptibility of the rotorcraft to entry into a vortex ring state at higher descent rates and slower speed. This occurrence must clearly be avoided. Both of these factors are associated with individual rotorcraft design characteristics and must be evaluated on a case by case basis.

A third factor related to wind effects on the approach and one which is more general, is the effect of wind on the available "inertial" performance of the aircraft. To examine this factor further, a second development of Γ_{eff} was performed in which the effect of wind was introduced by using a slant range, SR, calculated in air reference frame rather than earth reference frame. This recalculation reduces the slant range when a tail wind is present, thus increasing the geometric flight path angle Γ_o and increasing the flight path acceleration a_{fp}. Unfortunately the Γ_{eff} values generated by this revised formulation are extremely sensitive to the wind speed value used in the calculation, since the wind speed can be a large percentage of V_{DH}. This high sensitivity is not reflected in the flight evaluation results and therefore the original ground referenced development of Γ_{eff} (without wind related terms) is probably more appropriate.

Since a number of the evaluations were performed in the presence of tail winds, the handling qualities data from these approaches was investigated as a separate group. Figure 20 shows the handling qualities assessments for 9 degree approaches in which the tail wind component was measured to be larger than 5 knots, with handling qualities rating plotted against glideslope error and decision height velocity. While there is not enough data on this figure to entirely justify the boundaries for acceptable and satisfactory errors which were drawn from the general data base, the handling qualities evaluations made thus far *do not substantially conflict* with the boundaries. Further data gathering to investigate this issue is required.

7.0 Conclusions

Based on the data gathered over the course of this experiment, and the analyses discussed in this report, the following conclusions and observations can be made:

1) For the case of a decelerating approach on a 9 degree glideslope, the evaluations of the transition from instrument flight to visual flight and the manoeuvres required to establish a hover over the landing pad from the decision height of 50 feet show a strong relationship between the acceptability of the transition and the approach tracking errors present at decision height.

2) As noted in section 1.2 of this report, the majority of the data gathered over the experiment represented approaches for which the aircraft was too high or too fast at decision height. The acceptability of these types of error appears to be primarily governed by the available deceleration and descent performance of the vehicle.

3) The limited data representing cases for which the aircraft was too slow at decision height suggest that the acceptability of these types of error are governed by the dynamics of the vehicle for low airspeed flight.

4) Although in some cases there were reasonably large lateral errors in tracking at decision height (up to 50 feet), this aspect of the approach was deemed acceptable provided that the helicopter heading allowed the pilot to see the landing area at breakout.

5) The "window" of acceptable tracking errors at decision height for a 9 degree decelerating approach developed during this program was analyzed using an "effective flight path angle" concept, Γ_{eff}. While the tradeoff between excess speed and excess height does not appear to be governed by a constant value of Γ_{eff}, the use of this analysis does provide insight into the general tradeoff between the two variables, and it leads to a comparison of the acceptable error window to the rotorcraft available performance, through the Γ - V diagram.

6) The data gathered from the 9 degree approaches provides a basis to postulate the acceptable tracking errors for approaches using other nominal glideslopes. The limited data for the 6 degree glideslope approach *does not conflict* with this postulation.

7) The handling qualities data gathered using the IMC goggles to degrade visibility at altitudes below decision height is inconclusive due to the unrealistic simulation of poor visibility conditions.

8) The transition to the hover for the types of operations described here would probably benefit from landing pad lighting schemes which attract and direct the pilots attention to the centre of the landing area.

9) The handling qualities data gathered for approaches in the presence of tail winds is too limited to allow a firm conclusion on the effects of this variable.

Although these experiments were preliminary in nature and were intended to lay the groundwork for a more thorough second phase, nevertheless, a significant body of data was gathered over relatively few flight hours. Areas where further investigation is warranted include:

1) The effects of tail winds on the boundary of acceptable tracking errors.

2) Further confirmation that the acceptable tracking error boundaries for 9 degree glideslope approaches can be translated to other nominal glideslope approaches.

3) Flight tests with an aircraft possessing Γ - V characteristics significantly different from the Bell 205 to confirm the performance related characteristics of the acceptable tracking error boundaries.

8.0 References

1 Baillie, S., Kereliuk, S., Hoh, R., *An Investigation of Lateral Tracking Techniques, Flight Directors and Automatic Control Coupling on Decelerating IFR Approaches for Rotorcraft*, National Research Council of Canada Aeronautical Note NAE-AN-55, NRC No. 29604, October 1988.

2 Baillie, S., Kereliuk, S., *An Investigation into the use of Side-Arm Control for Civil Rotorcraft Applications*, National Research Council of Canada Aeronautical Note (numbers to be assigned) June 1990.

3 Sattler D.E., *The National Aeronautical Establishment Airborne Simulation Facility*, National Research Council of Canada Miscellaneous Report No 58, May 1984.

Table 1 : Evaluation Pilot Experience

Pilot	Total Hours	Rotary Wing Hours
RH	6500	200
SK	9000	1500
MM	8000	1500
EB	3500	3000

Table 3: Reduced Visibility Approach Rating Summary

Approach number	flight number	file number	pilot	g/s error (ft)	speed @ b.o. (knots)	loc error (ft)	HQR	g/s angl (deg)	wind speed (kts)	wind dir'n (degM)
108	25	2		19	21	40	7	9	9	336
109	25-2	1		4	30	28	6	9	10	316
110	25-2	2		19	20	43	6	9	10	319
111	25-3	1		15	29	35	6	9	10	326
112	25-4	1	rh	21	20	35	4	9	8	317
113	25-4	2		13	32	16	5	9	10	309
114	25-4	3		12	20	48	3	9	12	315
115	25-4	4		6	32	36	6	9	9	313
116	26	1	sk	5	20	37	3	9	9	281
117		3		0	33	26	5.5	9	7	279
118		4		6	10	16	5	9	7	286
119		5		11	12	26	4.5	9	6	280
120		6	rh	7	33	36	6	9	9	279
121		7		-6	46	-6	8	9	5	264
122		8		7	22	27	3	9	4	297
123		9		2	10	16	3	9	[illegible]	27[illegible]
124		10		18	21	20	5.5	9	3	264

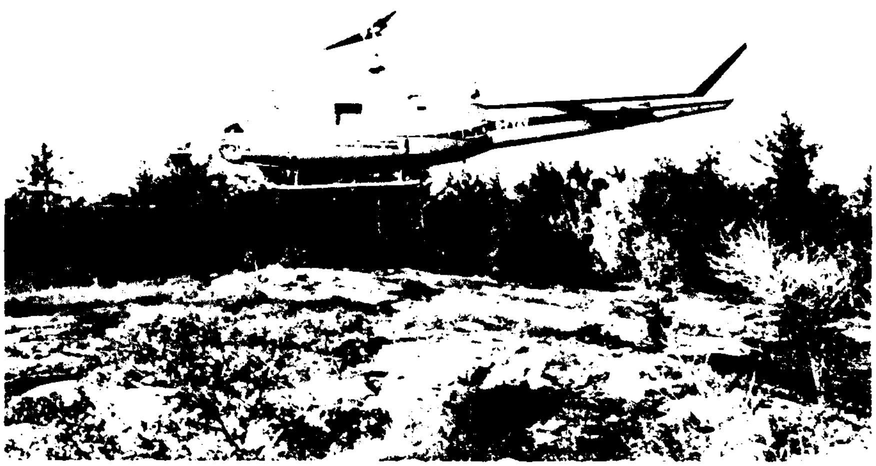

FIG. 1: THE IAR AIRBORNE SIMULATOR

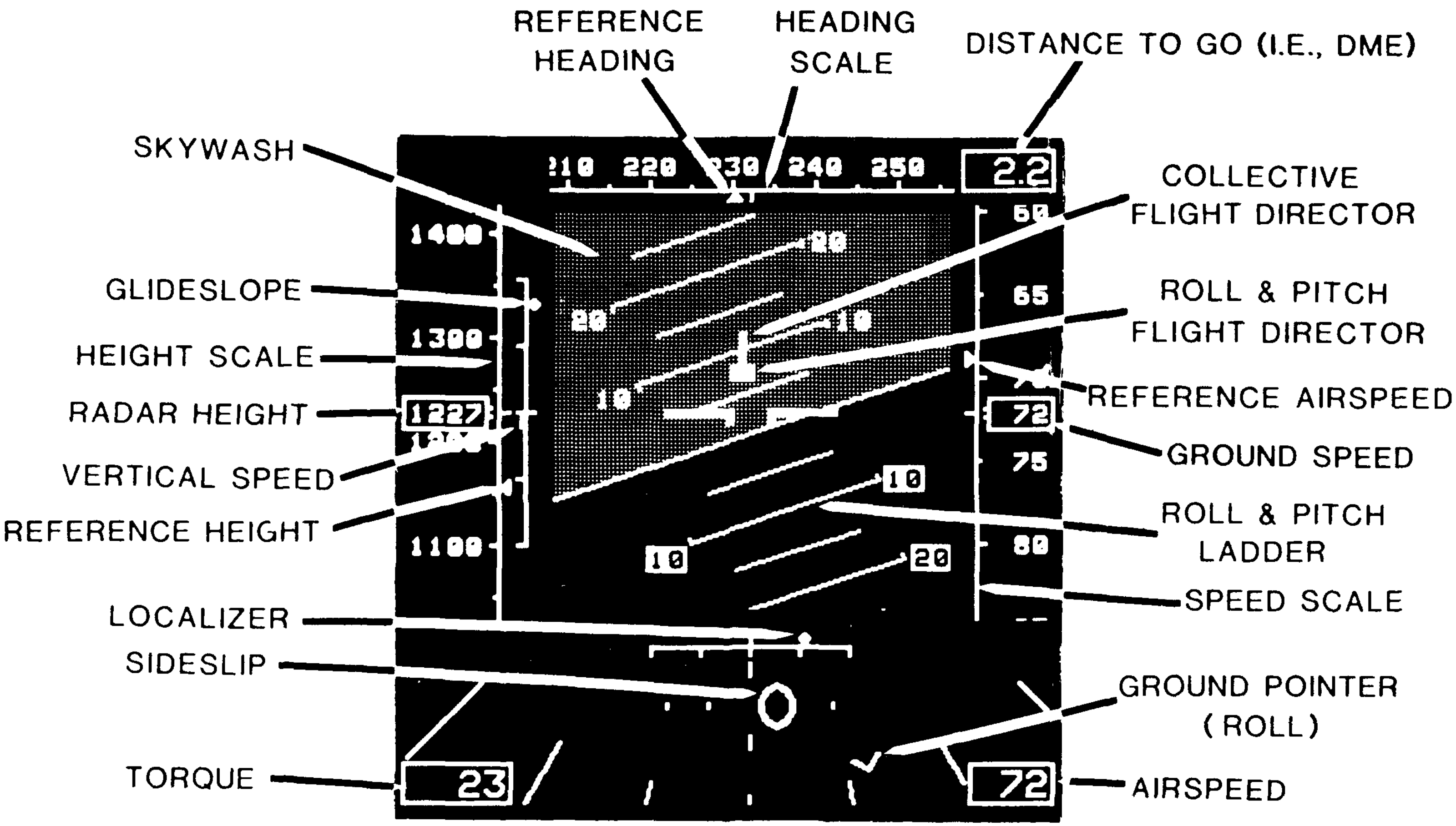

FIG. 2: ELECTRONIC DISPLAY SYMBOLOGY FOR IFR APPROACHES

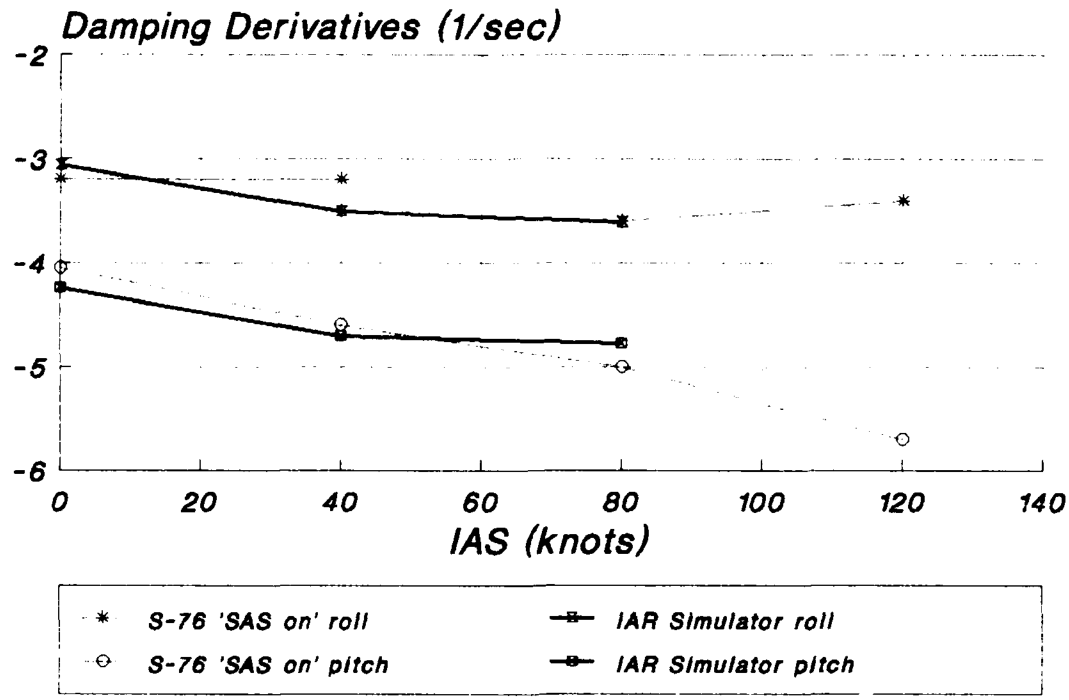

FIG. 3: DAMPING DERIVATIVES OF THE IAR AIRBORNE SIMULATOR

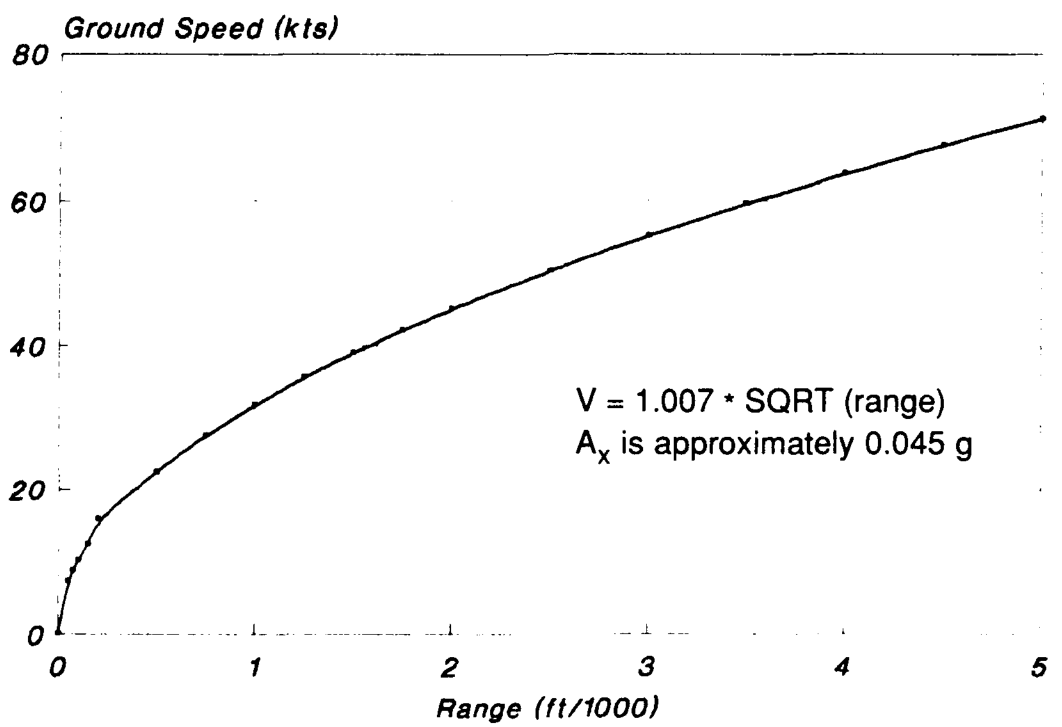

FIG. 4: PROGRAMMED DECELERATION PROFILE

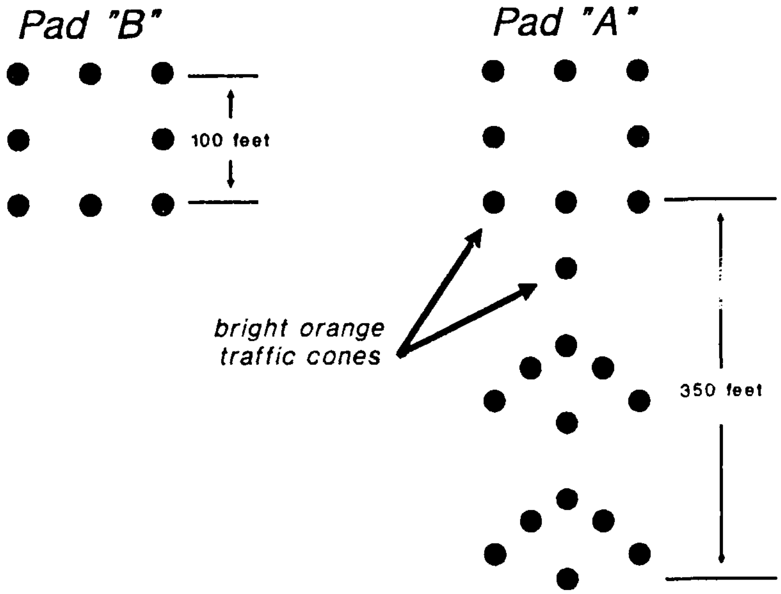

FIG. 5: LANDING PAD MARKINGS

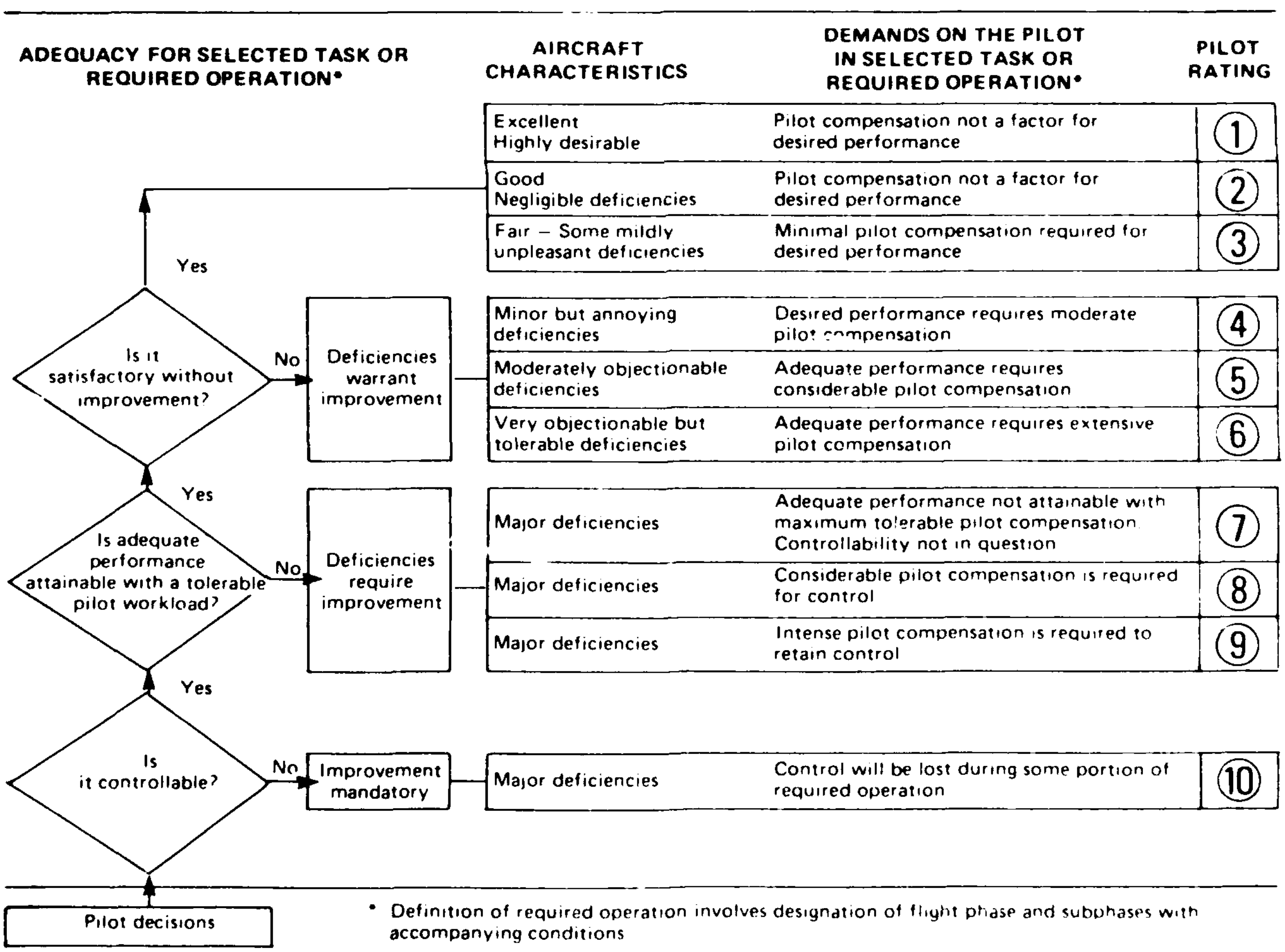

FIG. 6: THE COOPER-HARPER HANDLING QUALITIES RATING SCALE

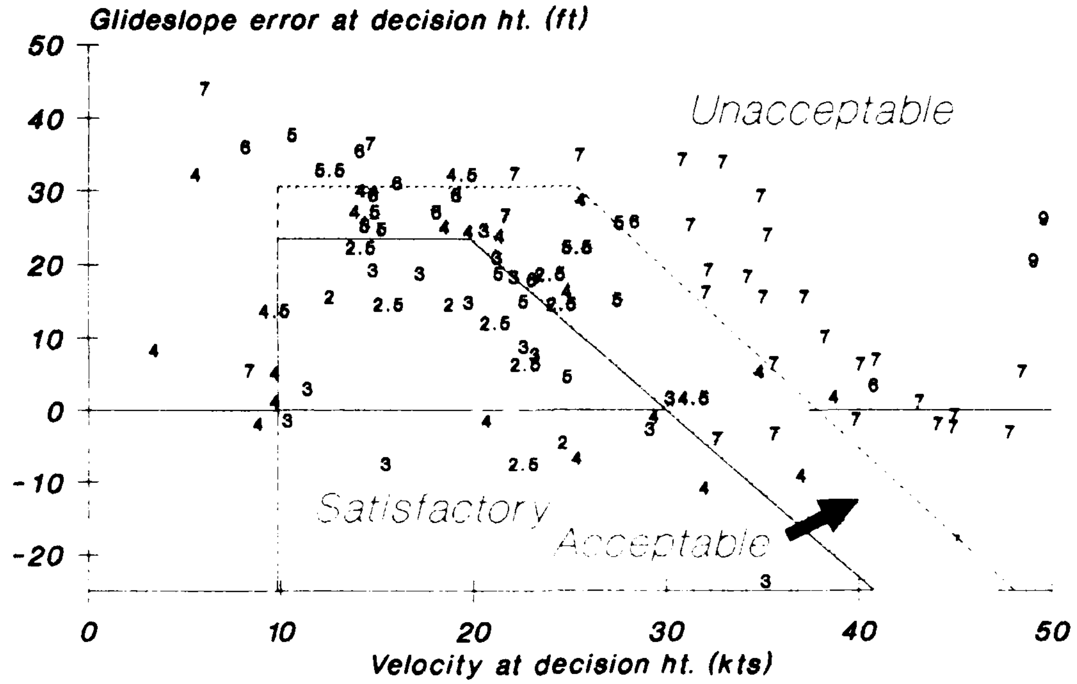

FIG. 7: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE DECELERATING APPROACHES

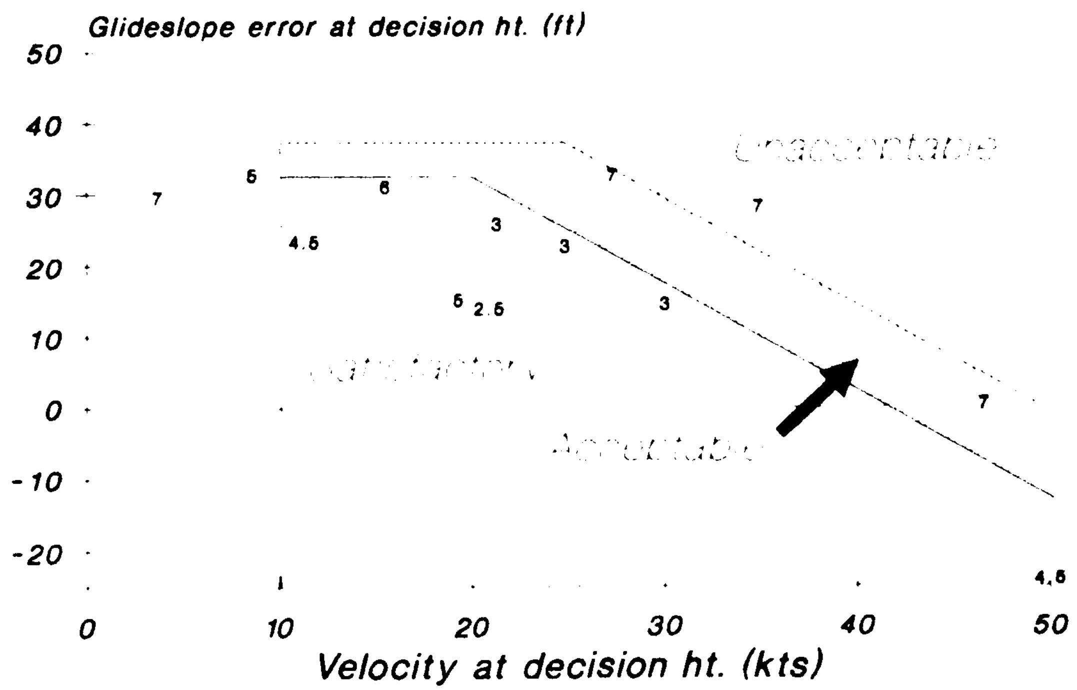

FIG. 8: HANDLING QUALITIES RATINGS FOR 6° GLIDESLOPE DECELERATING APPROACHES

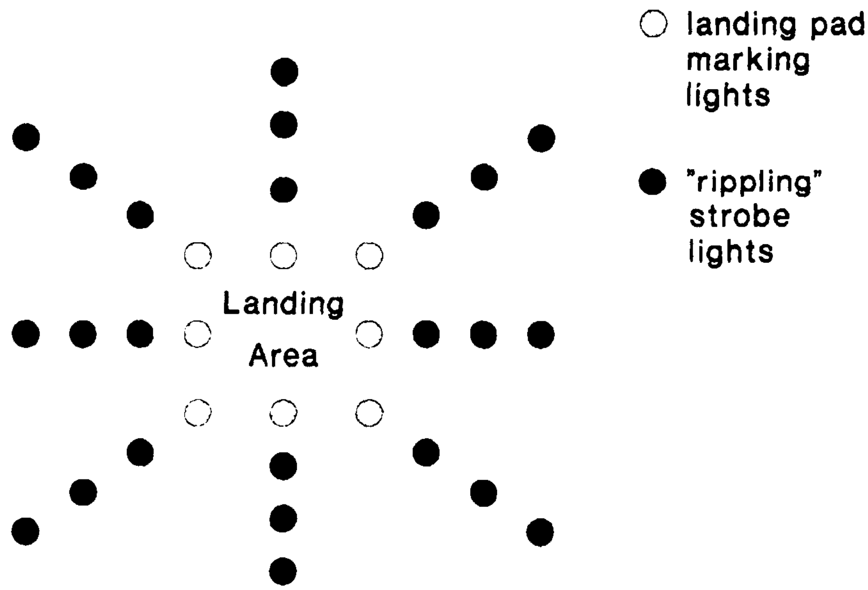

FIG. 9: SUGGESTED HELIPAD LIGHTING SCHEME

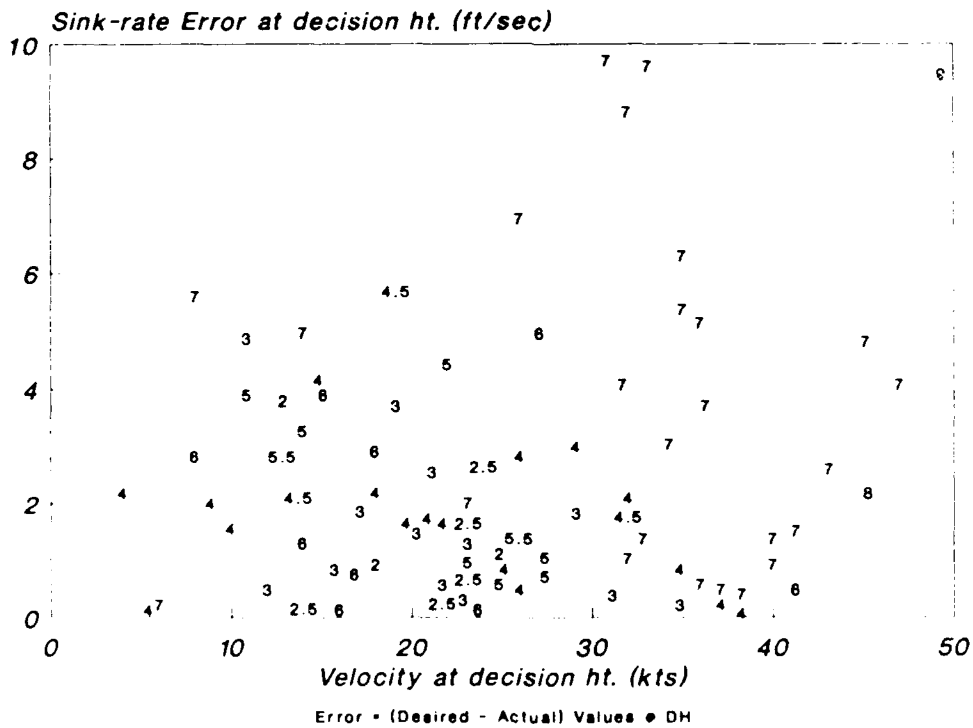

FIG. 10: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE APPROACHES COMPARED TO SINK-RATE ERROR AT DECISION HEIGHT

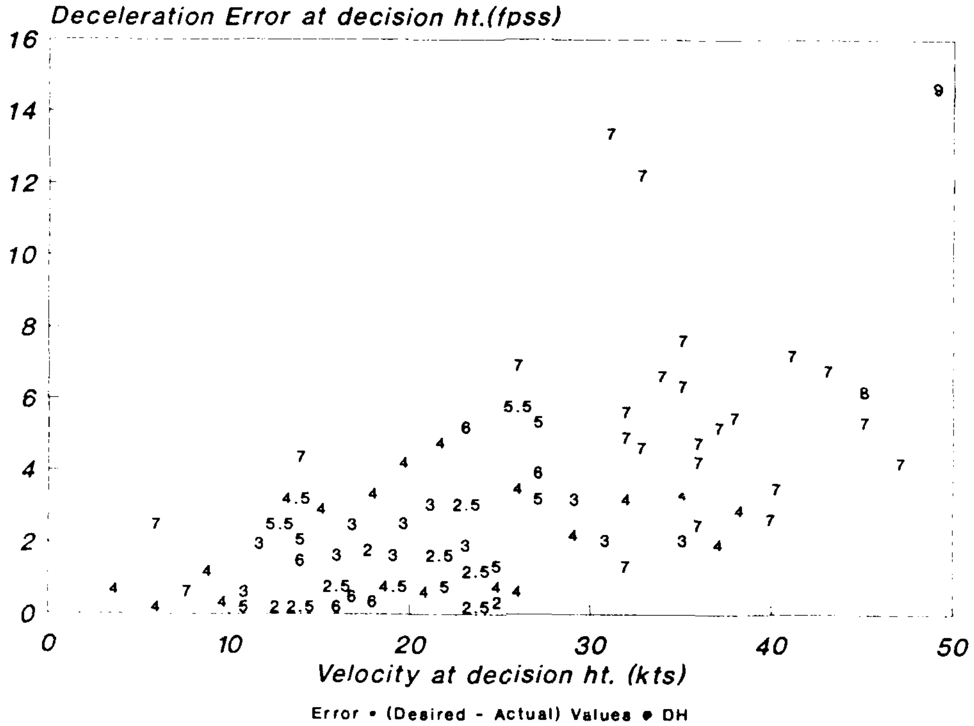

FIG. 11: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE APPROACHES COMPARED TO DECELERATION ERRORS AT DECISION HEIGHT

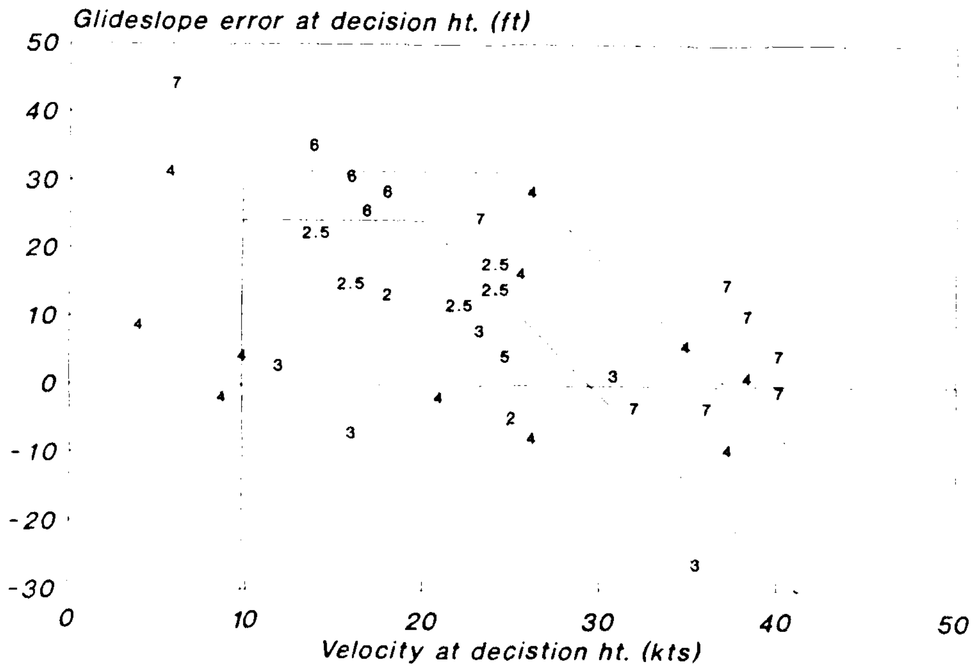

FIG. 12: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE APPROACHES WHEN $\Delta\dot{e}$ < 3.5 ft/sec

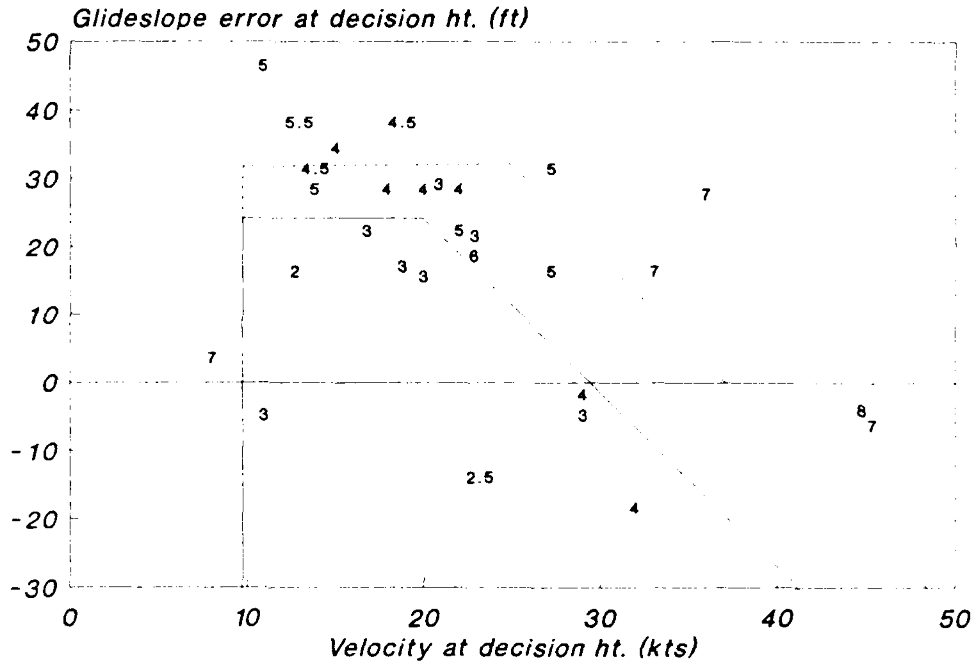

FIG. 13: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE APPROACHES WHEN 3.5 < $\Delta\dot{e}$ < 7.0 ft/sec

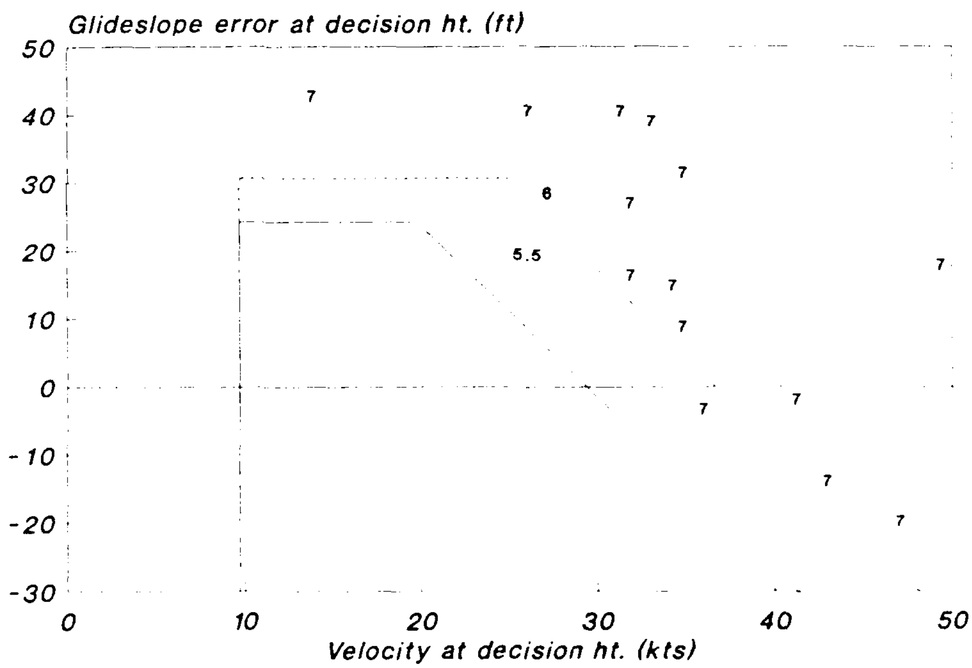

FIG. 14: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE APPROACHES WHEN $\Delta\dot{e}$ > 7.0 ft/sec

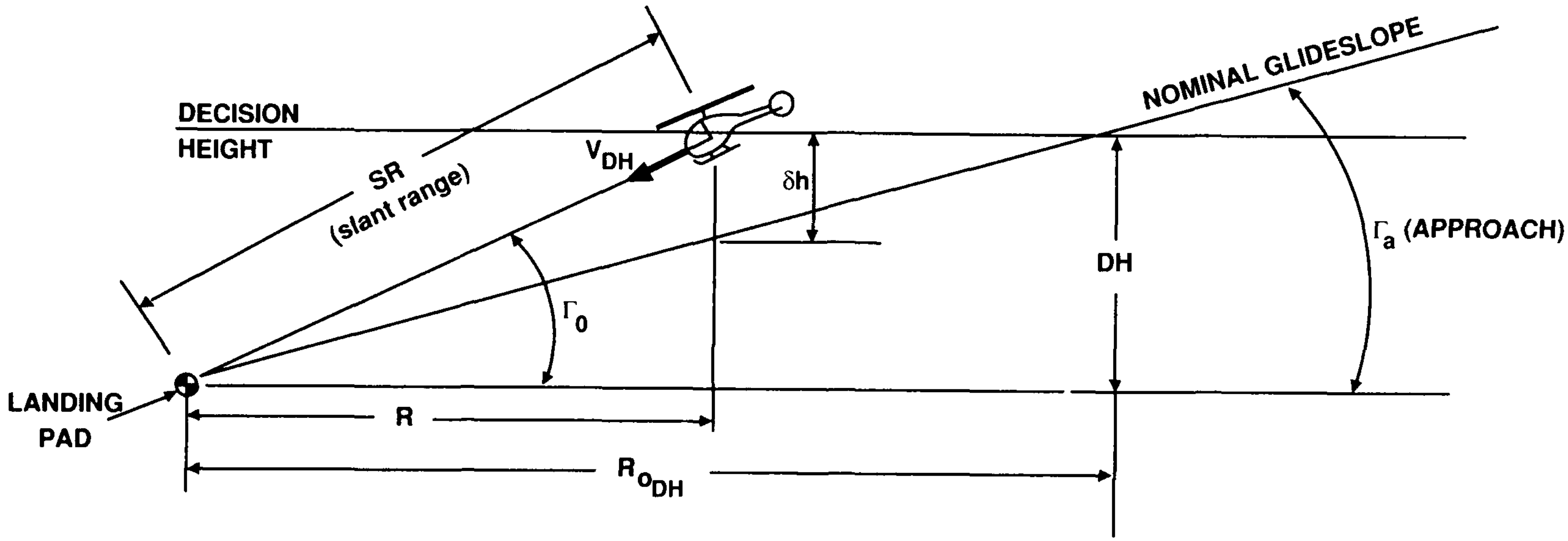

FIG. 15: NOMENCLATURE FOR THE DEVELOPMENT OF Γ_{eff}

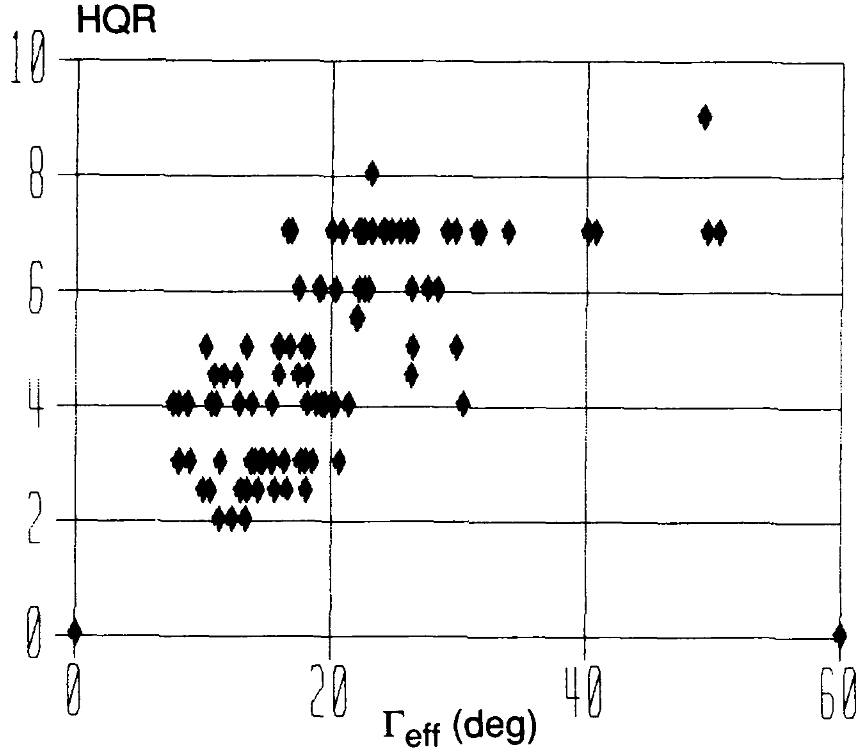

FIG. 16: EFFECT OF Γ_{eff} ON HANDLING QUALITIES FOR 6° AND 9° GLIDESLOPE DECELERATING APPROACHES

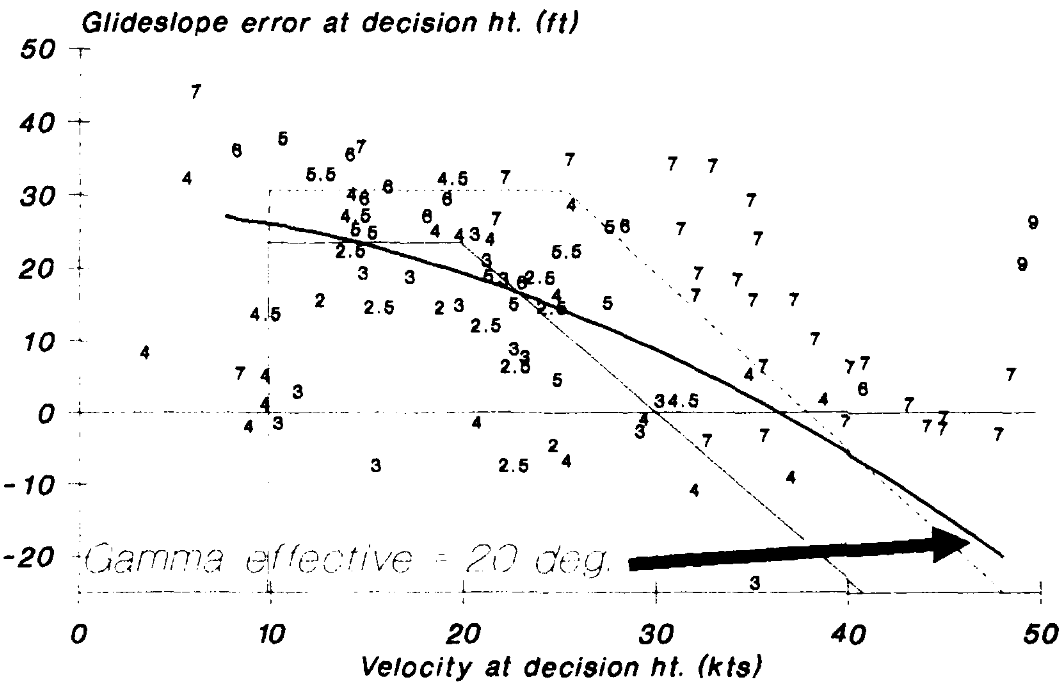

FIG. 17: COMPARISON OF EMPIRICAL HANDLING QUALITIES BOUNDARIES WITH CONSTANT Γ_{eff} CURVE (9° GLIDESLOPE DATA)

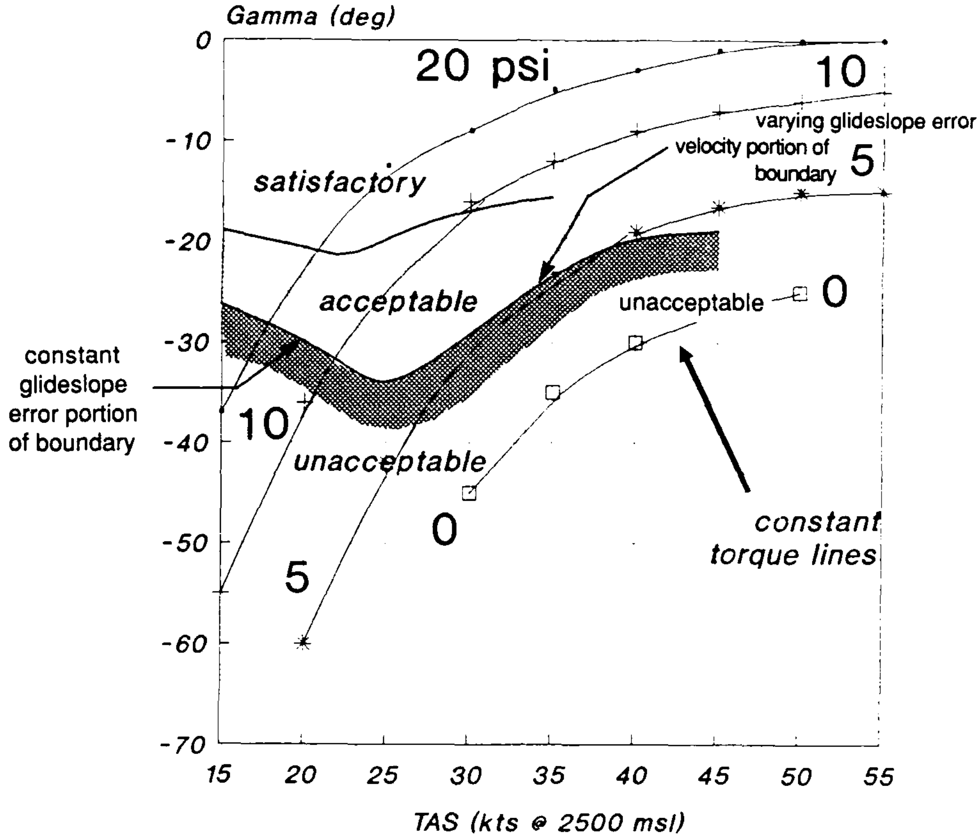

FIG. 18: EMPIRICAL HANDLING QUALITIES BOUNDARIES FOR 9° APPROACH TRANSLATED TO Γ_{eff} VALUES

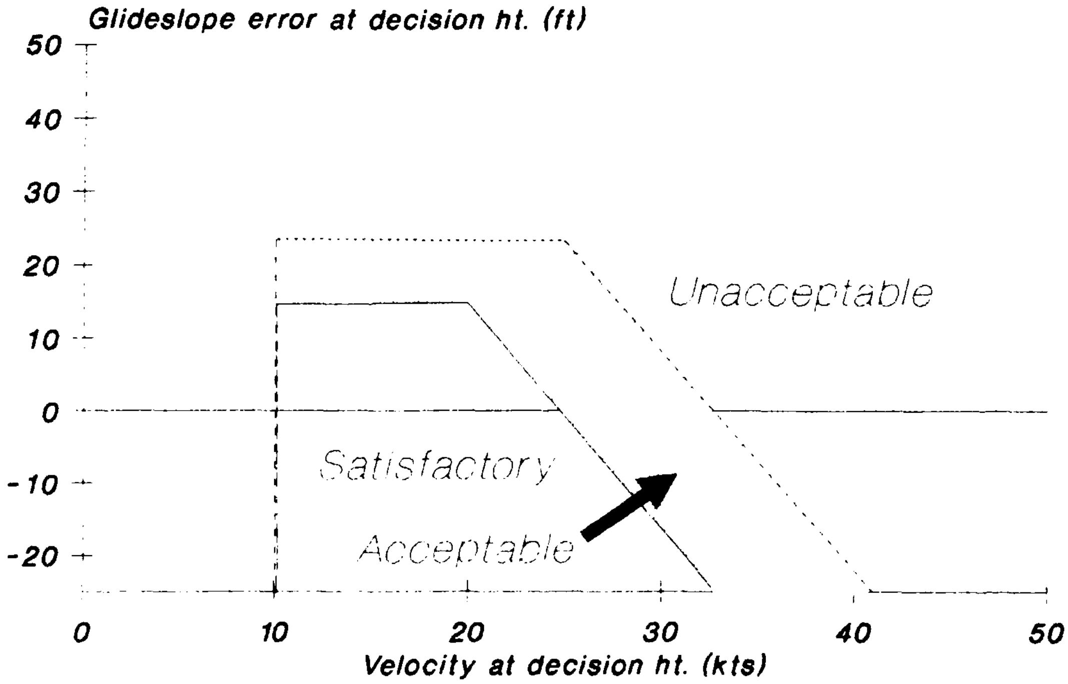

FIG. 19: POSTULATED TRACKING REQUIREMENTS FOR 12° GLIDESLOPE DECELERATING APPROACHES

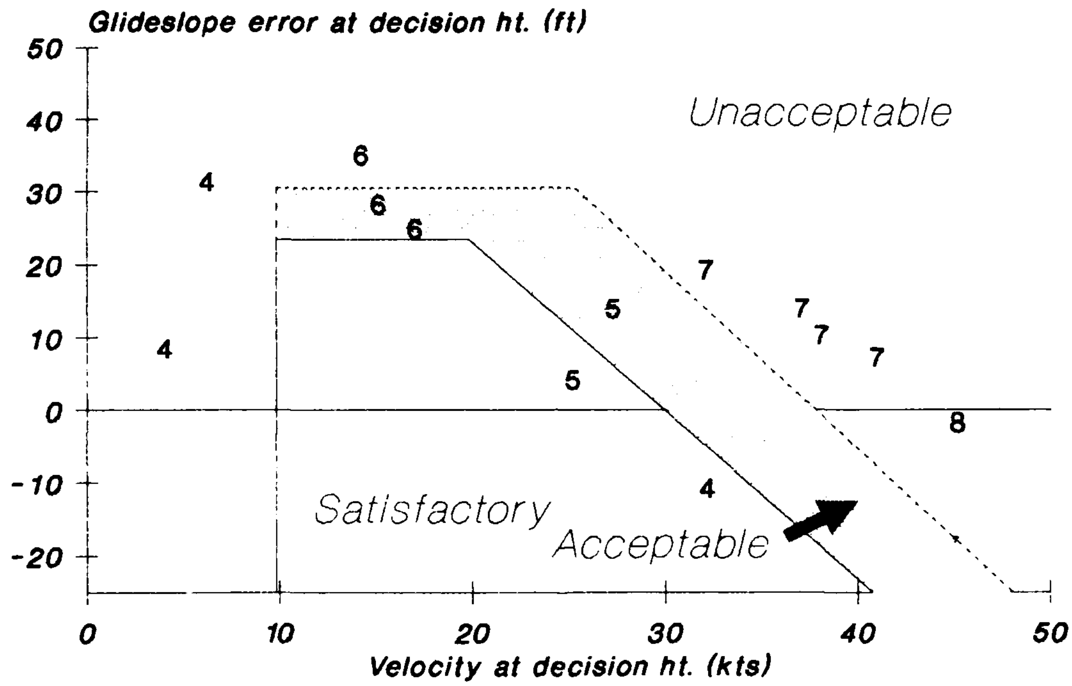

FIG. 20: HANDLING QUALITIES RATINGS FOR 9° GLIDESLOPE DECELERATING APPROACHES WHEN TAIL WINDS EXCEEDED 5 KNOTS

Appendix A

Pilot Comments for Evaluation Approaches 1 - 124

Approach Number	Pilot Comments
1	significant overshoot; went to maximum acceptable Θ and minimum δ_c; lost pad under nose; overshot pad-flight path out of control -7
2	overshot pad by about 50 ft.; used maximum acceptable aggressiveness on Θ and δ_c; came to hover open loop (like a quickstop)since at max Θ; lost pad under nose and drifted left since no cues for lateral alignment
3	no problem
4	no problem
5	overshot pad; Θ too high for this manoeuvre; might have been a little late on pitch up (flare); Hqr 7 due to Θ,δ_c inputs
6	no problem
7	no problem
8	coupled Θ and δ_c; Θ required not excessive; δ_c required seemed excessive - flared high; pad visibility fair - under nose some of the time; stopped at far end of pad; disengaged autopilot late >> quite far behind in flare
9	Θ and δ_c no problem; did not feel rushed; pad visibility good
10	Θ and δ_c required not a problem; pad visibility good; stopped at centre and 10 ft. altitude; not rushed
11	good; a little high
12	high and slow; noticeable vibration but not a primary factor (yet); steep approach; close to borderline; steep,vibration - possible vortex ring state, not comfortable
13	rapid deceleration, - close to maximum effort; flare was extreme; could not see far end of pad - used side of pad for guidance
14	no good!; stopped 50 ft past pad; used maximum Θ and held it
15	a little high but no problem; vibration annoying but not severe
16	a fair bit of δc required; no problem
17	slow deceleration- slight vibration, uncomfortable
18	as above
19	another slow deceleration; more vibration; pitch flight director gave problems at

break out; still acceptable

20 too high of closure rate!!

21 high!; Θ large but not excessive; moderate urgency

22 somewhat high; no problem; slight urgency

23 break out high and left; urgency, Θ moderate

24 NO GO!; low on g/s but too fast

25 OK - rapid deceleration and large positive δ_c; workload high; acceptable

26 a bit steep; vibration noticeable; getting closer to borderline

27 steep descent; moderate vibrations; high workload; reduced visibility would cause problems; h/v curve violation??; <u>borderline</u>

28 Θ δ_c moderately high, vibrations objectionable

29 Θ δ_c excessive

30 fairly aggressive but acceptable

31 very high closure rate; urgency extreme

32 vibration excessive, high breakout; unacceptable

33 no go ! ; steamed by pad

34 as above

35 steep and very slow; moderate vibrations and "bucking"; uncomfortable but acceptable

36 steep and very, <u>very</u>, slow!; vibration and "bucking"; ended up 100 ft. short of pad; excessive δ_c required; collective workload very high; too steep and slow!

37 very similar to above; collective flight director followed diligently; back end of pad; too steep and slow!

38 almost nominal; slightly fast and high

39 slightly fast, quite high; ended up in back 50% of pad; no vibration; quite steep; possible visibility problems

40 no real problems with height; speed seemed low, vibration noticed; stopped 100 ft. short

41 a bit fast; flare and stop easy, accurate

42 fast and high; ended up 100 ft. past the pad; too aggressive of flare required

43 same as above; went past by 150 ft.

44 fast and high; stopped at back of pad; excessive Θ; borderline but acceptable

45 overshot pad by 100 ft.

46 a little fast but no problem

47 almost an overshoot (by 2 feet!)

48 as above

49 high and slow; might be a problem in poor visibility

50 as above

51 aggressive flare required

52 very interesting, very easy approach!

53 like the last one, some Θ required for flare

54 a bit aggressive in the flare; watch for poor visibility case; >not borderline<

55 lost transponder signal during deceleration but regained it again prior to breakout; <u>acceptable</u>; broke out slightly to the right; stopped at pad centre

56 went by pad by 150 ft.

57 lost transponder again in approach; regained it late; went way past the pad

58 no way to stop before the fence!!!!

59 like approach #55; stopped at far end of pad; limit of acceptable

60 new flight director; lost transponder during deceleration; definitely borderline

61 almost made it!; just into the unacceptable region; over pad boundary at far end

62 a good one

63-68 - very strong cross winds from right side with big shear at 400 ft agl.- very unpleasant

63 no problem; some vibration but not excessive; good position and speed

64 no problem in transition; shear makes it very difficult to track speed and g/s during deceleration; approx 10° into wind offset used this time - too tough on airframe otherwise

65 very easy; gentle pitch correction and deceleration to have very natural - can not be worse than a "2" (noticeably steeper than the last two approaches)

66 less time available but still no problem; a/c position and speed was excellent; slight use of pitch and progressive up collective was all that was needed. Don't want to down rate because of approach conditions but cross wind and sun make it very difficult

67 steep but slow; transitional vibration before 50 feet which stopped almost as the goggles cleared; from 50 feet on down had absolutely no problem

68 seemed like run #65 same comments and rating

69 fast but OK; time short but set-up good so no real problem

70 very fast; not able to stop within the confines of the pad using as much attitude as I was prepared to do

71 Fast but OK; very good set-up; moderate θ; not level 1- I had insufficient time to end up exactly where I wanted to be

72 Slower but close in; no problem; good set up; broken goggles distracting down approach - affected tracking

73 fast, high and close!; 1/2 fuselage length beyond pad; HQR based on performance

74 moderate speed but very high; difficult to spot pad but Tx ok; ended up inside pad but not at the spot of choice.

75 high and fast; 3/4 fuselage length beyond pad

76 vibrations; slight problem seeing pad

77 same comments as above; plenty of time to stop however

78 difficult to tell when glasses unfog (switch setting?); high sink at bottom; made pad but power application intolerable

79 large flare but tolerable

80 high; made the pad but nearly lost sight of it under the nose of the aircraft

81 broke out short/high; took a few seconds to acquire pad (under the nose which was high); vibrations in close

82 some vibrations but not particulary objectionable; easy acquisition of pad

83 large overshoot of pad (50 + feet); late in power application

84 past pad by 10 feet; large flare

85 stopped short - taxied to pad

86 50-75 foot overshoot

87 some vibrations but acceptable; acquiring pad took a little time; power/control manipulations within acceptable range

88 +25 foot overshoot; not uncomfortable at bottom but clearly unable to make pad with maximum acceptable flare

89 fairly large flare but not unreasonable

90 made the pad but aircraft was gyrating fairly heavy upon power application; controllability not an issue

91 stopped high and short; did not break out initially; when power reduced, broke out and settled straight down to spot - flight director was calling for reduced power

92 same general comments as above but stayed with flight director; not as close to a "7" as above; lots of gyrating during "oge hover" portion of approach

93 made the spot, but very uncomfortable; high power/steep in close; nearly missed visual acquisition of pad; reluctant to lower power per flight director cue.

94 25 feet beyond pad; too fast; no way; too high

95 good; no Θ change to the pad

96 steep slow approach; vibrations ; could be a problem in poor visibility

97 slight flare required; could have easily stopped in centre of pad

98 steep slow approach; vibrations slight; could be a problem in low vis.

99 steep and slow; short of pad by 100 feet

100 a bit steep but ok

101 no comments

102 high; could be a problem with poor visibility

103 fast but low

104 just past pad by 25 feet; just past limit; could not see pad

105 same as above; high Θ; just past pad by 25 feet

106 No joy; 50 foot hover; galloping

107 high and hot; just past pad by 25 feet; high Θ

Approaches 108-124
obscured goggles at decision height and below

Approach Number **Pilot Comments**

General #108-115 goggles unrealistic in graininess vs. altitude cues; weak height cues - getting better as snow gets blown away from around pad; all approaches broke out on the right hand side of pad

108 bad one; lucky to see a pad marker in the chin window; no height cues; blowing snow?

109 black ice in centre of pad used as gross reference for pad position (*could not see pad markers*); ok but borderline due to closure rate and attitude required

110 reduced height cues - as opposed to Θ cues; high workload;

111 rapid flare and high Θ; borderline; better height cues

general comment by sk : speed increase may not make the ratings any worse

112 closure rate and sink rate cues both bad; conservative flare used

113 high on breakout; *moderate to high urgency*; *what to do?*; conservative flare used

114 no problem; on course, maybe low

115 fast at breakout; urgency high; maximum Θ used, lost in the flare; unacceptable

116 no problem; comfortable

117 broke out on right hand side of pad; very rapid deceleration; ok for stopping; approaching borderline

118 slow vibrations before and after breakout; HQR due to vibration level, otherwise a "3"

119 slow and steep; bad height cues; moderate vibration levels; HQR again mostly due to vibration

120 urgency high, unacceptable; lots of δ; very large Θ; not possible to stop

121 no problem; urgency - none

122 no problem; minor problem due to sun in goggles!!; couldn't see the pad

123 high at breakout; moderate Θ; moderate urgency; borderline

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4 Tracking Performance Requirements for Rotorcraft Instrument Approaches to Reduced Minima Phase 1 - Preliminary Study

AUTHOR(S)/AUTEUR(S)

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9	10	11	12a	12b

NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Rotary Wing Aircraft - Instrument Approach
2. Instrument Approach - Tracking
3. Tracking (Position) Performance Requirements

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SUMMARY/SOMMAIRE

The ability to track approach guidance (position and speed) to a low decision height (50 feet) when performing a steep instrument approach (6 to 9 degrees) in a rotorcraft clearly has a profound effect on the success of the approach. This report describes a preliminary attempt to define approach tracking standards for such approaches and includes a systematic data base upon which such standards can be based. This data base was generated in a flight experiment in which qualified rotorcraft certification test pilots evaluated the suitability of arriving at the decision height with various combinations of approach tracking error. The magnitude of tracking errors that are compatible with satisfactory pilot workload in the transition to hover and landing is well defined and tracking within these error bounds is clearly within the limits of current technology. The experiment was performed on the National Research Council of Canada's Bell 205 Airborne Simulator.

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